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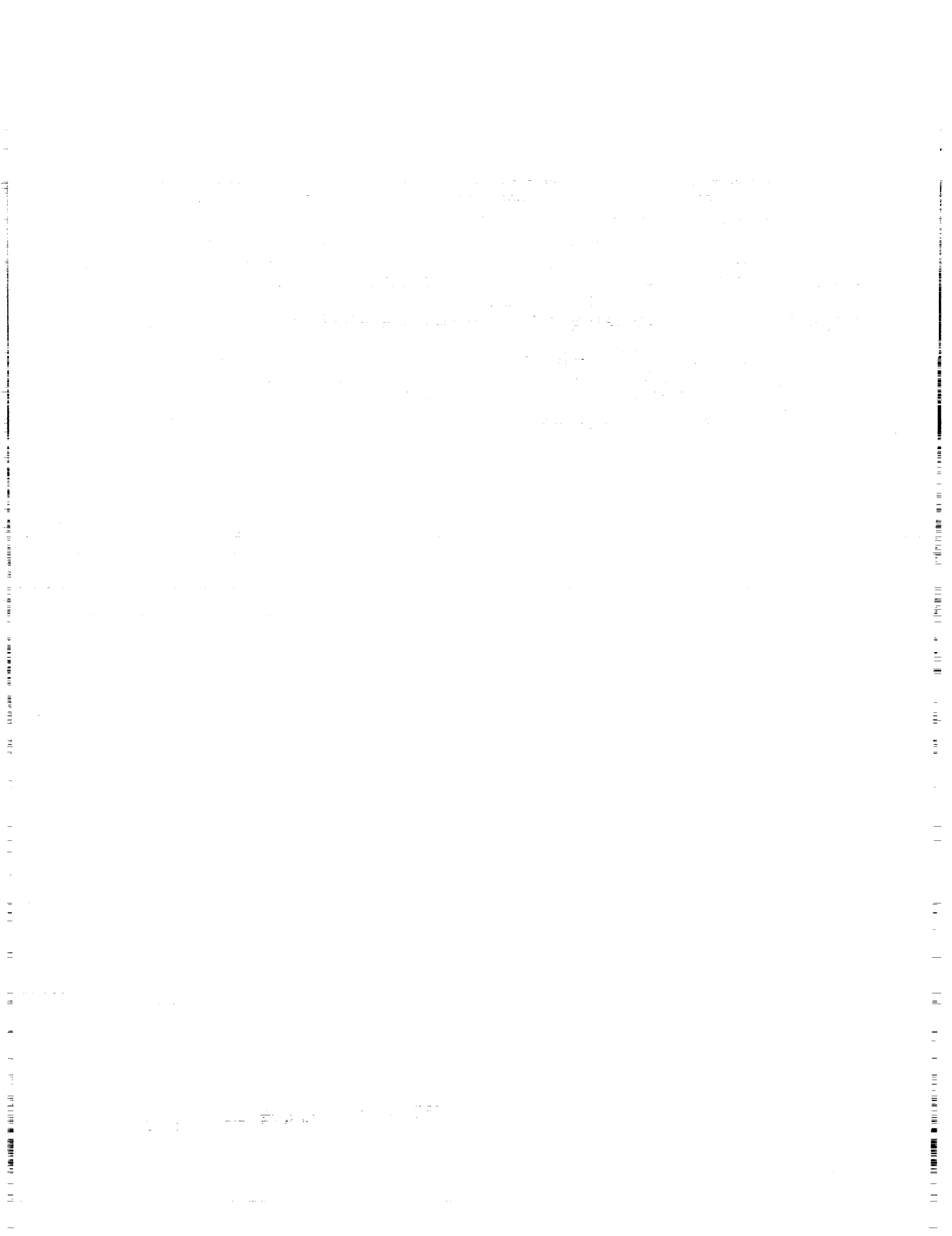
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ABSTRACT

The focus of this report is on the development and validation of a dynamic strength model for humans. Unlike earlier attempts at strength modeling, which were based on rotational spring and damper systems, this model is based on empirical data. The shoulder, elbow, and wrist joints were characterized in terms of maximum isolated torque, or position and velocity, in all rotational planes. This information was reduced by a least squares regression technique into a table of single variable second degree polynomial equations determining torque as a function of position and velocity. The isolated joint torque equations were then used to compute forces resulting from a composite motion, in this case, a ratchet wrench push and pull operation. A comparison of the predicted results of the model with the actual measured values for the composite motion indicates that forces derived from a composite motion of joints (ratcheting) can be predicted from isolated joint measures. Calculated T values comparing model versus measured values for 14 subjects were well within the statistically acceptable limits ($\alpha = 0.01$) and regression analysis revealed coefficient of variation (R^2) between actual and measured to be within 0.72 to 0.80.

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1.0 INTRODUCTION

Computer aided engineering (CAE) is commonly used in many aspects of aerospace engineering. Extensions and enhancements of this useful tool of analysis are now beginning to be applied to the complex area of human modeling. The overall goals include analyses of the performance capabilities of a given individual or population in a specific environment. This is a multifaceted problem. Anthropometric representations, kinematic articulation of joints (reach), vision, and strength are just a few examples of the areas of complexity involved. The focus of this report is on the development and validation of a dynamic strength model for humans.

A dynamic strength model could be used to assess and predict whether a person or population is capable of performing a physical task on the job. This is important in the case of space extravehicular activities (EVAs) where crewmembers need to handle massive structures such as satellites and various space assembly components. In these situations, mission planners would benefit from a simulation model of all the forces, torques, and accelerations that would be imposed by and on the crewmember.

Equipment design engineers could also benefit from a strength model. Design specifications can be enhanced if engineers could predict the forces and torques to be applied on or with a given piece of equipment. These applications include, for example, threshold torques needed to open hatches and doors and to operate tools needed for assembly or to determine maximum forces applied to ensure that the equipment will not be damaged. Equipment may be better designed if information on the strength of the user population were available.

Equipment placement designs and scenarios may also be enhanced. Questions like: "what is the best configuration for this body restraint relative to this tool for maximum strength," or, "where should this handhold be placed for the most efficient strength utilization" could be better answered by the systematic examination of many possibilities and scenarios with the goal of developing more comfortable and safer designs.

Lastly, a strength model is useful as a tool of study to achieve a greater understanding of how the musculoskeletal system functions, of how the torques and forces are propagated, and of what the system control mechanisms and parameters are. This knowledge may lead to better designs of robotic and manipulator systems of the future.

To date, a more comprehensive dynamic strength model in the literature has not been validated than the one developed here at NASA-JSC [1, 2, 3, 4]. Here are a few quotes from the conference proceedings of Human-Centered Technology, June 1991 regarding dynamic strength models [5].

Dr. Norman Badler, University of Pennsylvania: "We prefer that the user supply an acceptable strength model simply because ours is probably not very good."

Dr. Susan Evans, Vector Research Inc.: "The biomechanic strength models presented here reflect static controlled exertions. Performing dynamic exertions is the next step."

Brenda Thein, U.S. Army Human Engineering Laboratory: "[There is a need] for a dynamic strength model."

Dr. M. Ayoub, Texas Tech University: "Due to the complexity of dynamic biomechanical analysis, as well as the limited dynamic muscle strength data to compare with the task... [strength modeling] has been done with the aid of static models."

The purpose of this project is to develop and validate a physically based human modeling system which incorporates dynamic strength information into an anthropometrically correct human figure model. Unlike earlier attempts at strength modeling, which were based on rotational spring and damper systems, our model is based on empirical data. The shoulder, elbow, and wrist joints were characterized in terms of maximum isolated torque, or position and velocity, in all rotational planes. This information was reduced by a least squares regression technique into a table of single variable second degree polynomial equations determining torque as a function of position for a range of velocities (e.g., $\text{torque} = a + b * \text{angle} + c * \text{angle} ** 2$, where a, b, and c are the polynomial coefficients). The isolated joint torque equations were then used to compute forces resulting from a composite motion, that is, a ratchet wrench push and pull operation. The force torque calculations were dependent on the geometry of the human figures to convert the measured isolated joint torques to forces at the end effector. This required accurate anthropometric measurements. Presented here is a comparison of the computed or predicted results of the model with the actual measured values for the composite motion.

2.0 OBJECTIVE

Our objective is to develop and validate a human dynamic strength model for the upper extremity using empirical data.

Specific aims:

1. Document and describe all data processing techniques and algorithms used to validate the strength model.
2. Develop prediction equations to compute force for a multi-joint motion.
3. Validate the prediction equations of the dynamic strength model utilizing a multi-joint task (a ratchet wrench push-pull) using empirically collected data.
4. Implement a set of graphically based programs to demonstrate the flexibility and feasibility of this modeling approach.

3.0 METHOD

3.1 Data Collection

The data collection effort occurred over an 8-week period. There were 14 subjects, 8 males and 6 females, ranging in age from 21 to 28 years. Each subject was tested isokinetically for isolated upper extremity motion (shoulder, elbow, and wrist) at 4 angular velocities (60, 120, 180, and 240 deg/sec) and then tested with a simulated ratchet wrench maneuver at 2 angular velocities (120 and 240 deg/sec).

The general procedure for evaluating all the upper extremity joint movements was the same. Torque was measured using a LIDO active multi-joint testing unit (Loredan Biomedical, Inc., West Sacramento, California, Figure 1). The subjects were positioned so that the axis of the joint was directly in line with the axis of the dynamometer goniometer. Dynamometer attachments were selected and placed to isolate the joint being measured. The subject was positioned on the instrument and maximally stabilized with the joint positioned at a specified initial condition. The subject was then instructed to give a maximum effort for each of the five repetitions and to move the isolated joint through the entire range of motion. A 3-minute recovery period was taken before each change in velocity setting. The axes of motion measured were the shoulder flexion/extension, shoulder medial/lateral rotation, shoulder abduction/adduction, elbow flexion/extension, wrist flexion/extension, wrist radial/ulnar deviation, and wrist supination/pronation. The setups for these motions are described in the LIDO multi-joint testing manuals.

For the multi-joint test, a ratchet wrench maneuver, the subject was stabilized with velcro straps at the waist and across the chest. The subject gripped a simulated ratchet device at a height of 90% of the linear distance measured from the subject's greater trochanter to the acromioclavicular joint. The range of motion for the ratchet bar was between 40 and 50 degrees. To minimize the motion of the upper extremity, the subject extended the elbow and shoulder fully forward without bending at the waist. This test was also a maximum torque effort of 5 repetitions with a 3-minute recovery period before each change in the velocity setting (120 and 240 deg/sec).

The anthropometric data which were collected included height, weight, age, sex, skin fold measures, and dimensional assessment. The anthropometric data format is documented in NASA Man-Systems Integration Standards (MSIS) document (NASA-STD-3000) [6]. The standard was also used to provide the joint limit information. Joint limits for the model were applied statistically as this information was not collected in our study [4].

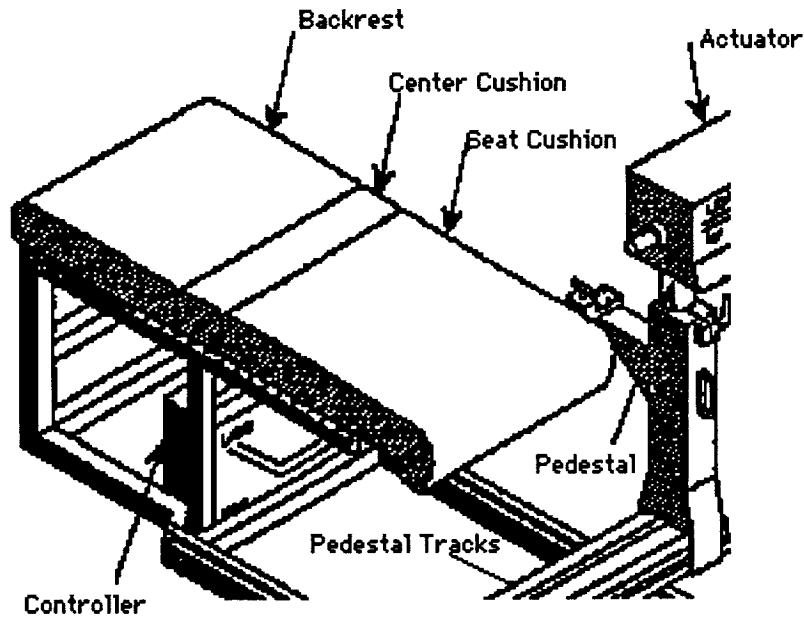


Figure 1. LIDO multi-joint testing system.

3.2 Data Reduction

A set of streamlined programs was developed to process the raw strength data (produced directly by the LIDO force torque dynamometer) into a compact polynomial coefficient format. The raw data were collected using the LIDOACT software executing on an IBM PC. The files produced on the PC were transferred to the VAX system using a data communication software package (Kermit) in binary mode. These data were then transferred to a UNIX-based workstation.

After being separated into files by subject, velocity, direction, and degree of freedom for each joint, each torque versus angle data file was viewed graphically and edited for extraneous data points. Figure 2 shows that the initial and final portions of the curves were edited out. The rationale for filtering out the initial and final portions of the torque curves was that for all isolated joint motions there is a startup time during which the subject is beginning to apply a maximum torque. At the end of a motion, the subject was anticipating the stopping and change of direction of the LIDO actuator arm. These transition regions of torque were inconsistent and so were not part of our modeling effort.

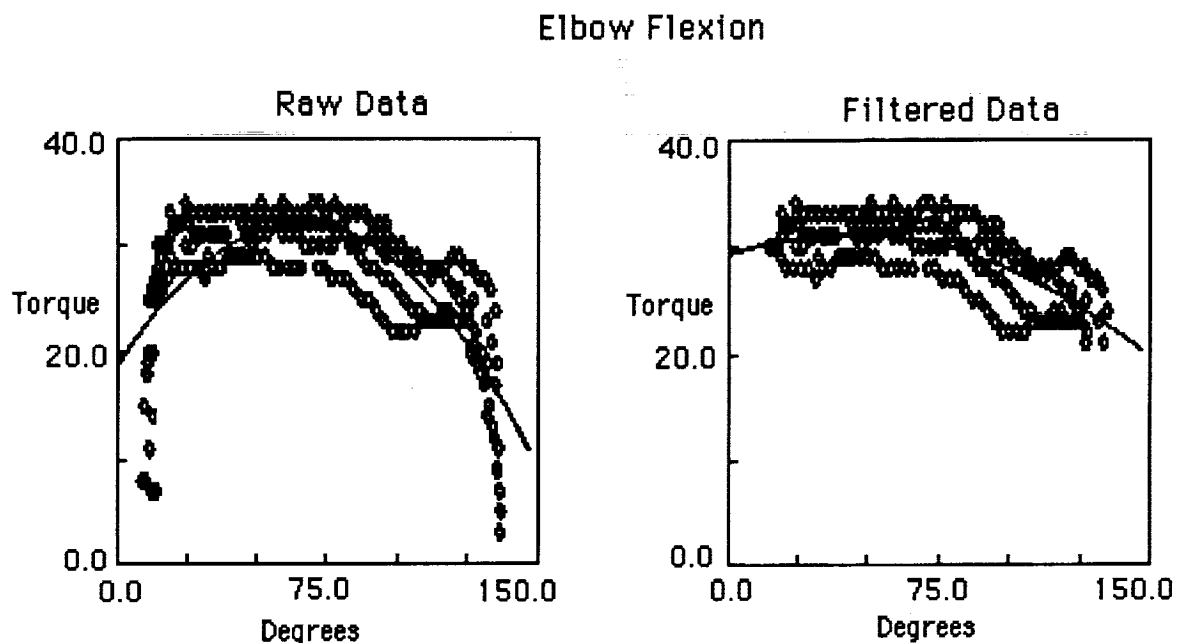


Figure 2. Data before and after visual editing.

The following is the flow of data from raw LIDO files to a torque function coefficient file (Figure 3).

1. The UNIX uncompress command uncompresses the data files needed.
2. The UNIX "ls" command feeds a list of the file names (one at a time) to the lido program.
3. The lido program converts each file it receives from the LIDO format into an ASCII format and passes the data (one file at a time) to tosort.
4. The tosort program computes the regression equations and collates person data and passes that condensed data on to the sort program. In addition, it creates x-y files of force versus angle and stores them for review later.
5. The sort program sorts the data on each field and passes the data to the toffc program.
6. The toffc program processes sorted data to produce files in the torque function coefficient format (Figure 3).
7. The original data is then recompressed to conserve disk space.
8. The x-y files are moved into a separate directory called xy.
9. All the unnecessary files are cleaned up.

```

right_shoulder /* joint name*/
x              /* axis */
abduction      /* direction*/
4              /*number of velocities*/
/* 1 velocity , 3 polynomial coefficients. note: Y = A + Bx + Cx**2 where A,B,C are the coefficients*/
60.000000      3.477892E+01      2.220639E-01      -2.821324E-03
120.000000     5.058879E+01      -1.974063E-01     -2.446309E-04
180.000000     3.441185E+01      -2.165272E-02     -1.170670E-03
240.000000     4.630580E+01      -2.306546E-01     6.999267E-05
adduction
4
60.000000      3.899835E+01      -2.004480E-02     -1.001798E-04
120.000000     3.210880E+01      6.244854E-02     -3.269533E-04
180.000000     1.128712E+01      4.013751E-01     -1.763708E-03
240.000000     2.879990E+01      -4.255312E-02     6.872315E-04
y
extension
4
60.000000      1.853307E+01      1.233500E-01     -1.150867E-04
120.000000     1.598296E+01      2.713108E-01     -9.975418E-04
180.000000     1.516010E+01      2.109192E-01     -8.056303E-04
240.000000     9.103311E+00      1.325615E-01     -4.602912E-05
flexion
4
60.000000      6.689232E+01      -4.941486E-01     1.258664E-03
120.000000     4.769003E+01      -2.906334E-01     8.198689E-04
180.000000     5.670030E+01      -4.014365E-01     1.149240E-03
240.000000     4.729467E+01      -3.183639E-01     8.940246E-04
z
lateral
4
60.000000      1.650289E+01      -4.517265E-02     -5.588200E-04
120.000000     1.434598E+01      -2.340409E-01     -2.806892E-03
180.000000     1.873110E+01      -1.003202E-01     -1.389751E-03
240.000000     1.489092E+01      -4.907729E-02     4.311464E-04
medial
4
60.000000      2.395702E+01      1.128039E-01     -1.947907E-04
120.000000     2.124104E+01      1.564447E-01     -3.186225E-03
180.000000     2.144591E+01      1.826617E-01     -1.797236E-03
240.000000     1.980874E+01      1.336217E-01     -8.705539E-04

```

Figure 3. An example of the coefficient file format for input into the strength model.

This process of transforming LIDO data files to force function coefficient files (ready for model input) is completely automated with very little user intervention [4].

3.3 Anthropometrically Correct Figure Creation

To simulate physical tasks using the strength model it was necessary to create computer representations of the human bodies measured. The models were fully articulated human representations with proper segmentation of the body parts and statistically determined joint limits. The body representations were based on the figures developed by the University of Pennsylvania [7]. The human figure representation has 22 body segments. Figure 4 shows the correlation between the human skeleton and the computer-generated figure.

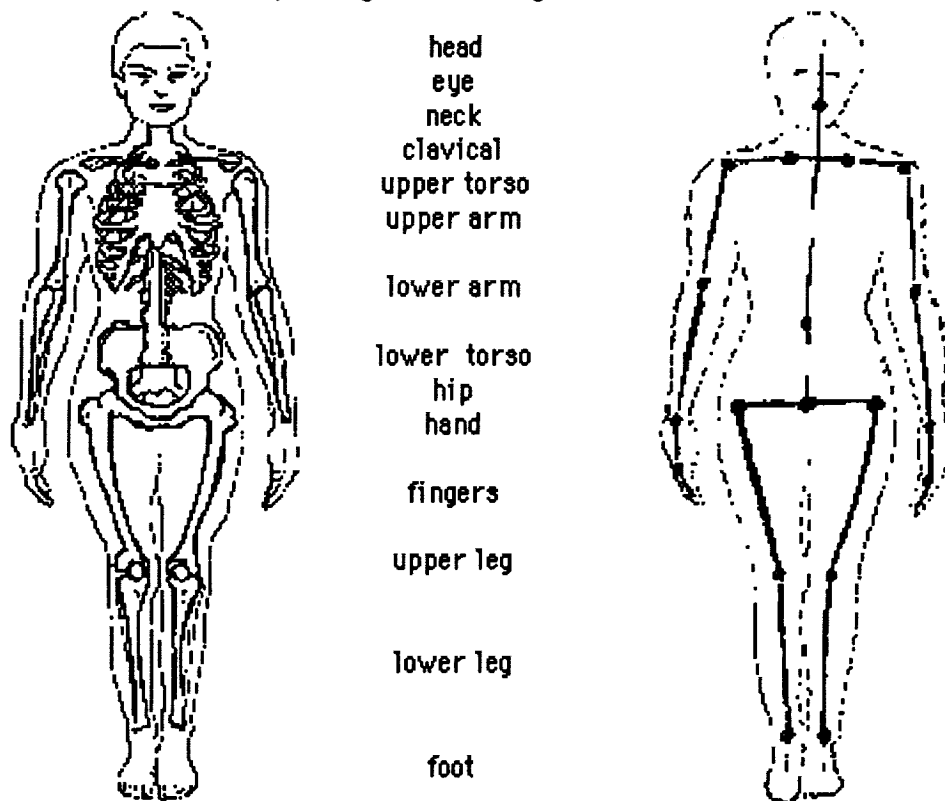
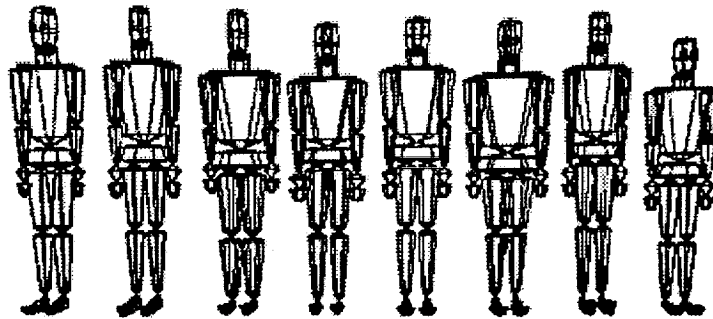
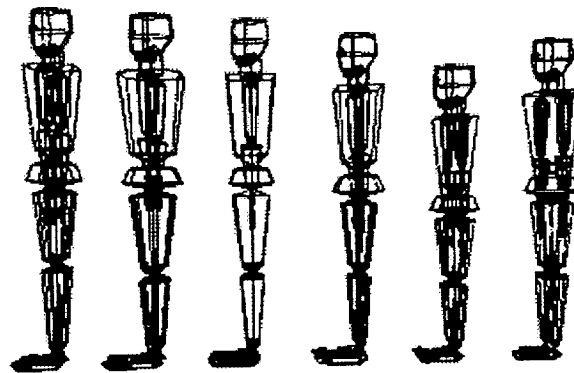


Figure 4. Correlation between human skeleton and computer-generated figure.

Anthropometric measurements were made on 14 subjects. These subjects were measured while standing with arms at their sides and palms facing forward. Length, width, and depth measurements of the body segments were made using a cloth measuring tape. From these measurements, a jointed computer model of each subject was generated. Figure 5 shows the eight male and six female computer-generated figures. In addition, for each subject, weight and skin fold measurements were recorded. These data were used to calculate the lean body mass for each individual (Table 1).



Front view: male subjects.



Side view: female subjects.

Figure 5. Computer-generated figures.

SUBJECT	SEX	AGE	Height (cm)	Weight (kg)	%Body Fat	Lean Body Mass (kg)
1.	M	23	173	64.9	10.4	58.2
2.	M	25	178	76.0	10.4	68.1
3.	M	28	188.3	84.5	14.5	72.2
4.	F	23	172.3	77.2	29.5	54.4
5.	M	22	185.0	88.2	10.7	78.8
6.	M	25	180.0	86.0	5.7	81.1
7.	M	26	176.3	95.2	19.0	77.1
8.	F	23	174.0	60.6	18.6	49.3
9.	F	22	168.0	59.1	14.8	50.4
10.	F	21	158.5	46.4	17.2	38.4
11.	F	21	158.0	51.6	19.5	41.5
12.	M	21	178.5	80.7	8.9	73.5
13.	F	23	166.0	55.7	20.8	44.1
14.	M	23	162.5	68.5	11.3	60.8

TABLE 1. Summary of Subject Pool.

In general, the computer representation reproduces the differences in the subjects. However, there is an overall trend in the generated figures to be, on average, 5% taller than the actual height of the subjects. This was due to accumulation of errors in the measurements since each joint segment was measured independently. To reduce this problem in the future, it is recommended that all segment length measures be made from a common reference point (e.g., the floor).

To check for inconsistent measurements or to quickly obtain anthropometric measurements of a subject, an alternate measurement procedure was developed. Video images of the front and side views of a subject were taken. These images were then processed with image processing software developed to extract segment length. Figure 6 shows the video images of one subject along with computer figures generated from video images and measured data.

3.4 Environment Setup

Each individual was created in the graphics environment using that individual's anthropometric data (Figure 3). The initial conditions of the ratcheting operation were set to match, as closely as possible, the actual conditions. This was a critical step for validation. The main parameters of the initial conditions included the initial and

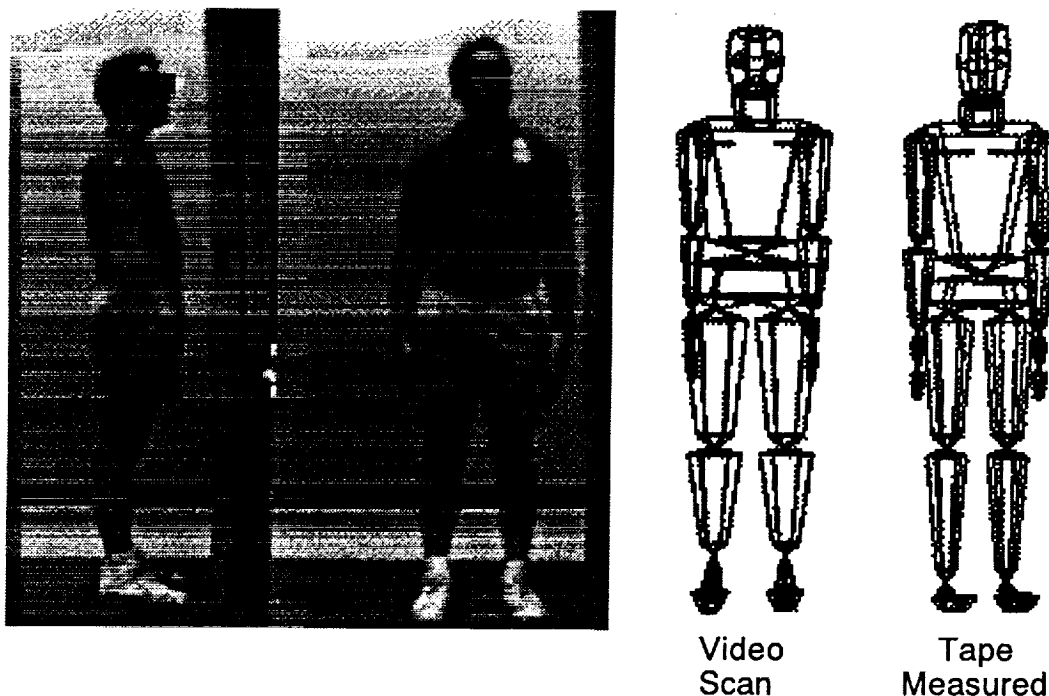


Figure 6. Video image of subject with computer figures.

final joint angles for the ratcheting motion, the distance of the hip from the rotation point of the ratchet axis, the height of the end effector on the ratchet, and the orientation of the end effector (hand) on the ratchet handle. Using the graphics environment, all these initial conditions were set for each individual prior to the

execution of the computer simulation of the ratchet operation (Figure 7). There is an uncertainty with regard to the orientation of the end effector position. End effector orientation information was not collected at the time of measurement. Hence, video images and mockups of the ratcheting procedure were analyzed to extract the orientation. This orientation varies over the range of the ratchet motion and between subjects. Since the actual orientations were not measured, data were taken at 2 orientations (120 and 140 degrees with respect to the ratchet handle). End effector orientation information, in retrospect, was very important because it affected the entire joint chain and the kinematic solutions. It will be measured in all future experiments.

3.5 Modeling the Motion (Inverse Kinematics)

To model the reaching characteristic of the arm while operating the ratchet bar, an inverse kinematics algorithm was needed to solve the joint angles of the arm

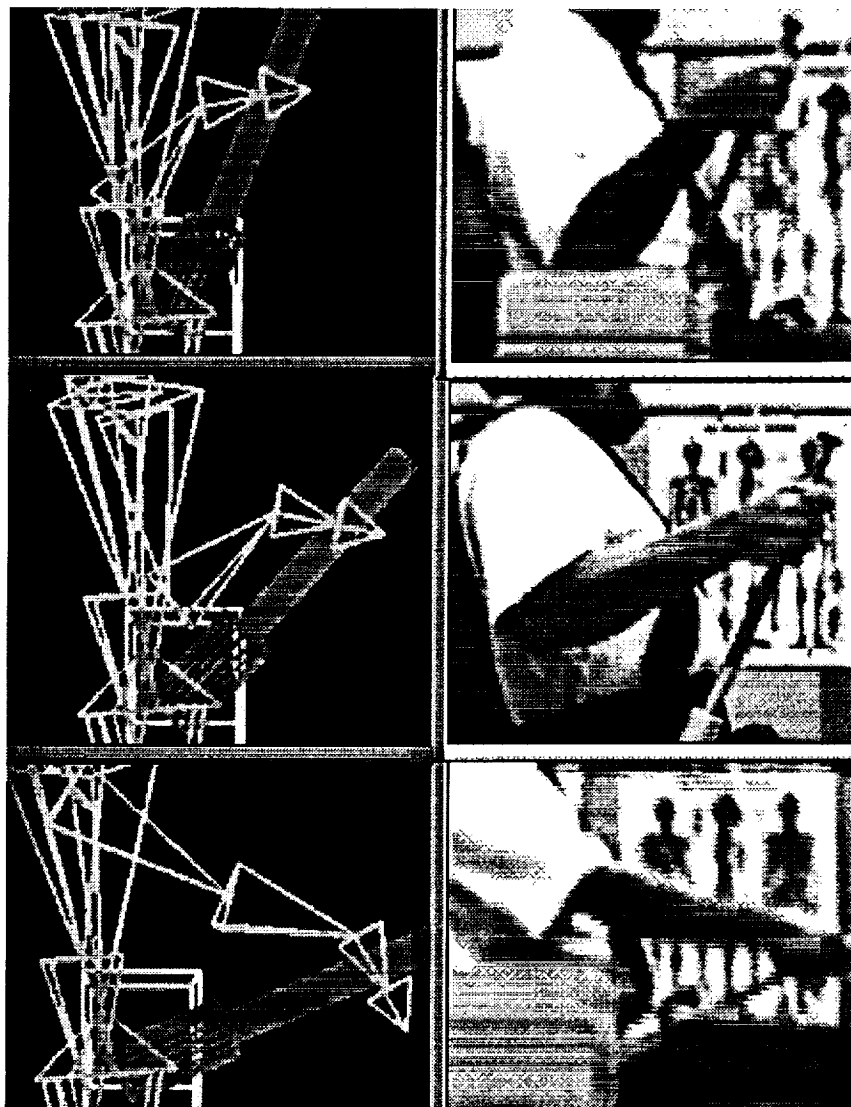


Figure 7. Model versus actual ratcheting.

[8, 9, 10, 11]. Also, the human model with its corresponding anthropometry needed to be accessible to the force modeling software to integrate the torque functions with the motion of the arm. A software package named Jack [7], developed at the University of Pennsylvania, was used as a platform for our strength model. Although many enhancements and modifications were required, the underlying inverse kinematics and anthropometrics implementation permitted us to model the required motion.

The simulation of the ratchet bar motion consisted of the following sequence of events.

1. The parameters of the motion (start angle, end angle, steps to take, and velocity of the ratchet) were input.
2. Time sequence information was computed which satisfied all the conditions of the ratchet's motion.
3. The location of the joint chain forming the arm and the location of the point of application on the ratchet bar were graphically selected.
4. Using the joint chain information, the torque functions for each component of the arm were loaded into the force model for use during the iterations of the ratchet operations.
5. The ratchet was moved to its initial or next position and the inverse kinematic module was invoked to grasp the point of application on the ratchet with the specified end effector (palm) in the joint chain.
6. The state of all the components of the arm, the joint angles of the arm, and the state of the ratchet were extracted and input to the force model where the torque prediction was computed and written to an output file.
7. Steps 4 and 5 were repeated until 5 iterations of pushing and pulling were completed (Figure 7).

To validate the reaching motion calculated by the inverse kinematics algorithm, a real-time magnetic tracking system was devised for input into the algorithm. The tracking system consisted of a Polhemus isotrack magnetic tracker (Polhemus Navigation Sciences Company, Colchester, Vermont) connected to a Silicon Graphics workstation (Silicon Graphics Inc., Mountain View, California). The magnetic tracker was linked to the end effector of the human-model representation. As the tracker was moved in space by a person, it fed the position and orientation information of the end effector to the inverse kinematics algorithm. This information was then used to simulate the motion of the person's arm in the computer model. The tracker of the Polhemus device was attached to a bar which could be rotated the same way the ratchet bar was rotated. Comparison by visual inspection of the actual motion of a person's arm performing a ratcheting operation with the graphically emulated motion computed by the inverse kinematics algorithm showed a strong correspondence (Figure 8).

Figure 9 shows a human-model representation operating a ratchet tool. Displayed along with the figure are the force torque vectors and bar charts showing the torque at each joint of the joint chain selected.

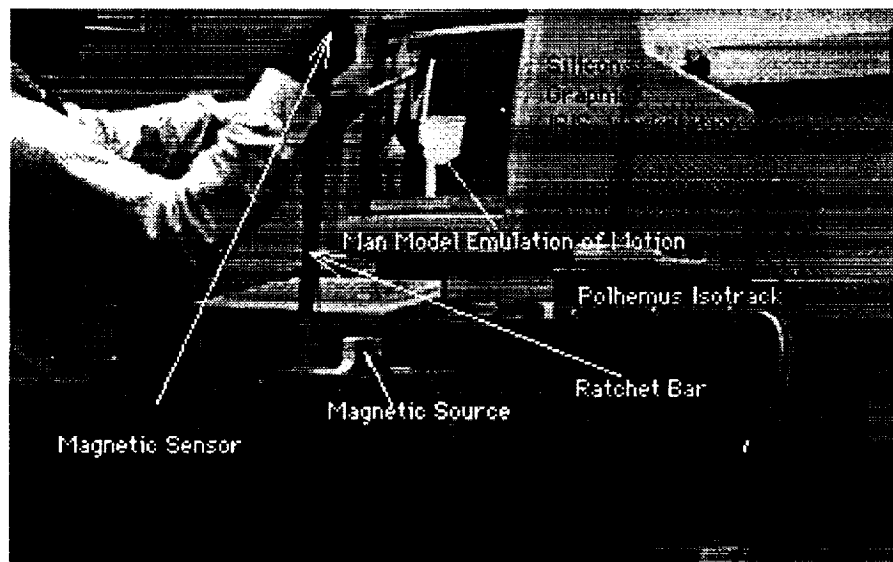


Figure 8. Real-time motion emulation with a magnetic tracking system.

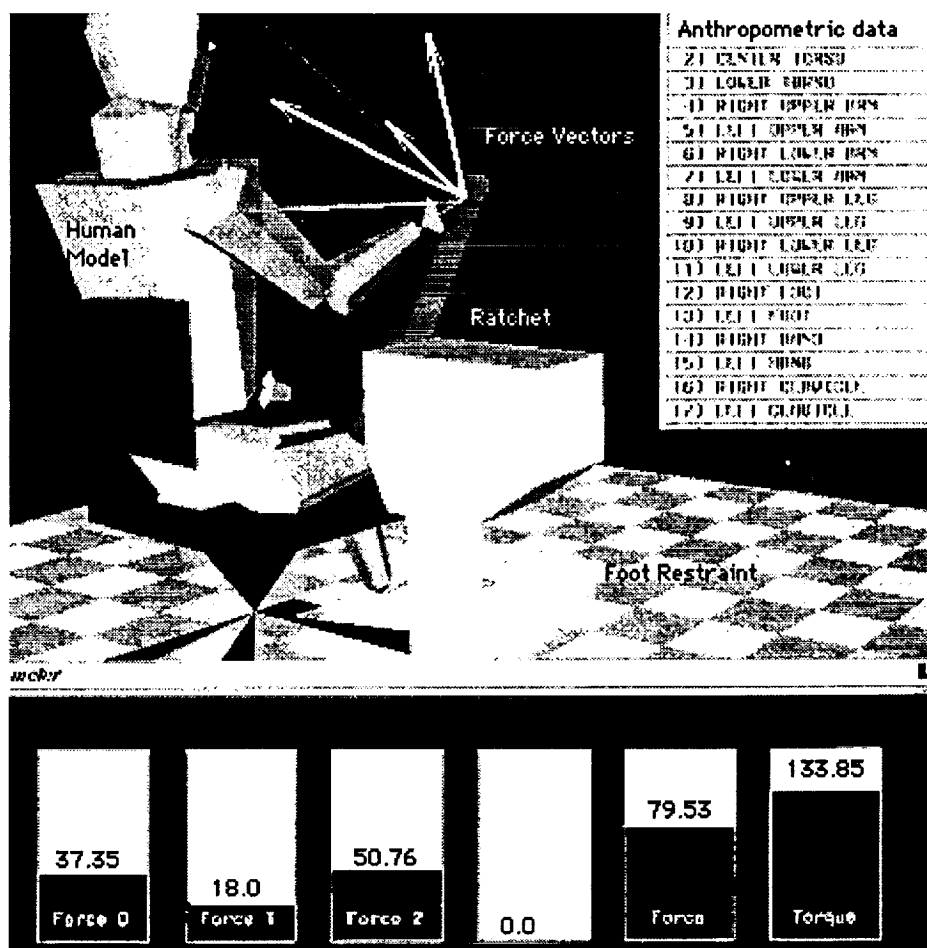


Figure 9. Human-model representation operating ratchet tool.

3.6 Torque Vector Calculation

Each joint of the upper extremity was associated with a table of polynomial coefficients describing its dynamic torque production potential [4] (Figure 3). In the modeling process, the tables were loaded into computer memory for use by a table look-up module. When a joint motion occurred in our test case, the axis of motion, direction of motion, angle of motion, and speed of motion were mapped to the appropriate polynomial and a torque value returned.

Since it is assumed in our model that each axis of rotation for a particular joint is perpendicular to each other axis for that joint, the square root of the sum of the squares was used to determine the available torque for each joint involved in that motion.

$$T_s = \text{sqrt}(t_x*t_x + t_y*t_y + t_z*t_z)$$

where

$$\begin{aligned} T_s &= \text{total torque for shoulder} \\ t_x &= \text{torque for x axis} \\ t_y &= \text{torque for y axis} \\ t_z &= \text{torque for z axis} \end{aligned}$$

The torque values at the other joints were similarly calculated.

For each joint, the lever arm to the point of application of the force, in this case the palm, was determined (Figure 10). This is the Euclidean distance from the location of the center of rotation of that joint to the end effector. The torque values for each of the joints were converted into forces at the end effector by dividing out the respective lever arm lengths for the shoulder, elbow, and wrist (L_s , L_e , L_w).

$$\begin{aligned} F_s &= T_s / L_s \\ F_e &= T_e / L_e \\ F_w &= T_w / L_w \end{aligned}$$

The direction vectors for each of these forces ($\langle F_s \rangle$, $\langle F_e \rangle$, $\langle F_w \rangle$) were also computed at each iteration of the motion. Each vector was computed by taking the cross product of the current lever arm position with the lever arm position at the previous iteration and then crossing the resultant vector with the current lever arm position. This computation produces a direction vector of motion ($\langle F_s \rangle$, $\langle F_e \rangle$, $\langle F_w \rangle$) for each of the individual joints.

The force values were then applied to the respective direction vectors of rotation and vectorially added to produce the total end effector force vector, $\langle F_t \rangle$. $\langle F_t \rangle$ represents the total force at the end effector from the contributions of all joints in the chain.

For the test case, $\langle F_t \rangle$ needed to be resolved into a torque value at the ratchet axis. This was done by first projecting $\langle F_t \rangle$ onto the normalized direction vector of rotation, $\langle R_t \rangle$, for the ratchet bar yielding a vector $\langle F_{\text{proj}} \rangle$ in the direction of rotation of the ratchet bar with a magnitude representing the force applied in that direction. This force

was then multiplied by the lever arm length of the ratchet, the distance from the point of rotation to the point of application (L_r), yielding a torque value, (T_r). This torque value and the current angle of rotation of the ratchet bar were written to a file. In addition, $\langle F_t \rangle$ and $\langle F_{proj} \rangle$ were graphically displayed.

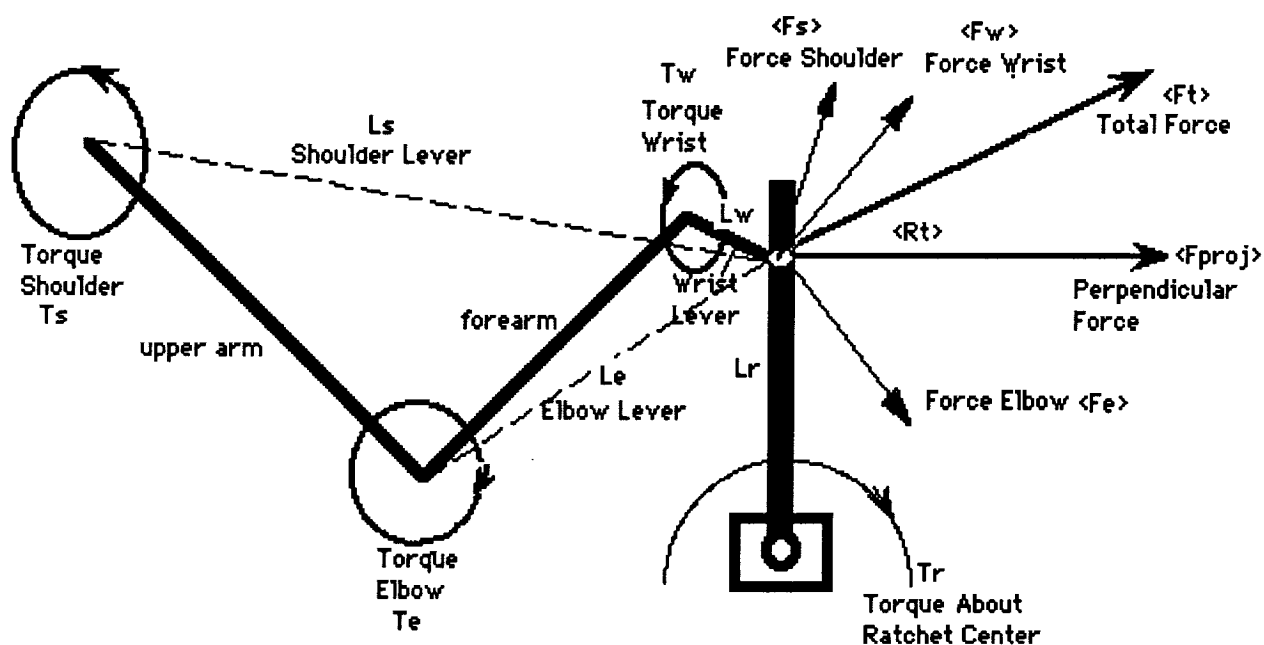


Figure 10. Diagram illustrating the force vector propagation.

4.0 DATA ANALYSIS

All the subjects were run in the graphics environment with initial conditions and orientations closely matched to the actual runs (Figure 7). The ratcheting was modeled at the same velocities as the measured data (120 and 240 deg/sec). Outputs from the model were files of torque versus angle pairs in the same range of angle values as the measured ones. For both the model output data and the measured ratcheting data, the average torque produced and the total work done per iteration were computed. These data were the basis of the validation of the model. Statistical analysis was done in two forms: pairwise T tests and regression analysis [12, 13]. Software was written to do these tests in an automated way without user intervention.

For the T test, the measured versus model files of the averages and total work done over all subjects were read and a difference vector was created. This difference vector was the basis of the T test comparison. Our hypothesis was that there was no difference between the model and the measured values when comparing either the torque averages or total work done. The following explains the pairwise T test that was computed.

$ud(\text{difference}) = u(\text{model}) - u(\text{measured})$
(where u is the average torque or the total work done for each subject)

null hypothesis (H_0): $ud = 0$ ($u(\text{model}) = u(\text{measured})$)
alternate hypothesis (H_1): $ud \neq 0$ ($u(\text{model}) \neq u(\text{measured})$)

Hence, the decision rule is to reject H_0 if:
 $T(\text{computed from the data}) < \text{critical value } 2.46$ ($\alpha = .01$)

The regression test was simply a way to gauge the correlation between the actual and measured values. We plotted the model average torque versus the measured average torque for all subjects and did a linear regression on that data set. The same analysis was done on model versus measured work. In addition, plots of actual versus measured raw torque values were also produced.

5.0 RESULTS AND DISCUSSION

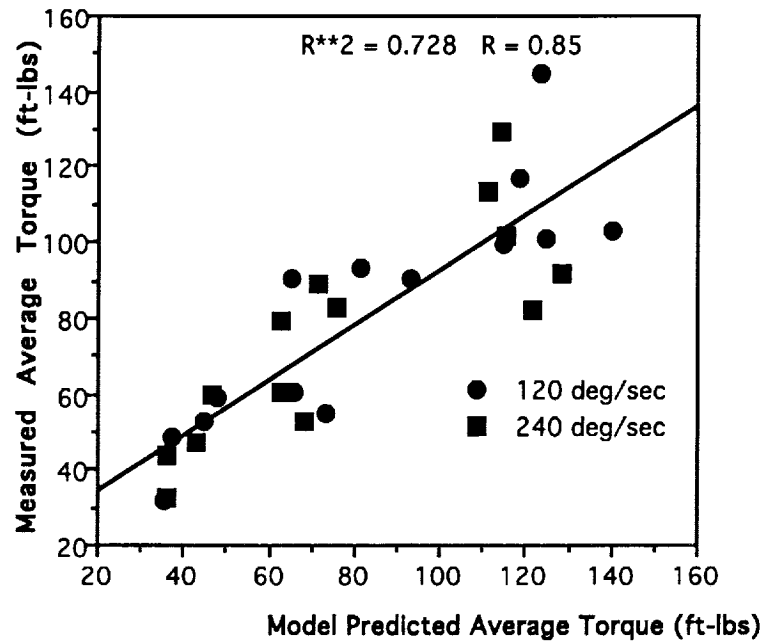
Regression plots of model versus measured average torque and model versus measured total work are shown in Figures 11 and 12. The correlation coefficients ($R^2 \sim 0.75$) indicate a strong relationship between measured and model values. This result indicates that the model can be used as a good predictor of the ratchet wrench torque produced when the model versus measured values are compared for the entire subject pool in terms of the average torque produced and the total work done.

In addition to a regression comparison of the average torque and work done over the range of the motion, a pairwise T test was also performed on that data. The results (Table 2) indicate that for the ratcheting motion the model predicted and measured torque values show no statistical difference across the subjects at a level of alpha equal to 0.01.

	Push	Pull
Average torque	T = 0.51	T = -1.69
Total work	T = 1.23	T = -0.99
H0 is accepted because all T values calculated are within +/- 2.47 (the critical value at alpha = 0.01).		
See also the pairwise T test analysis on page 16.		

TABLE 2. Pairwise T Statistic Results of Average and Total Work Across All Subjects for All Velocities.

Ratchet Push- Model vs. Measured Average Torque



Ratchet Pull- Model vs. Measured Average Torque

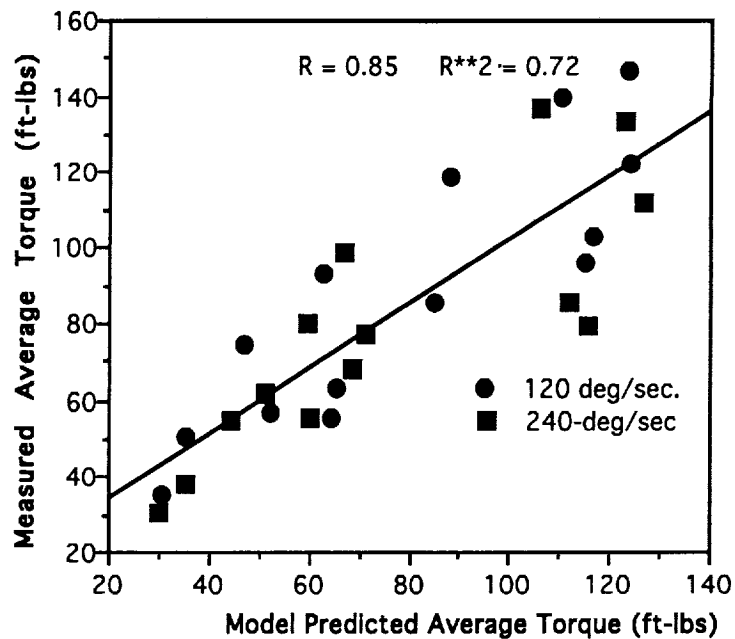
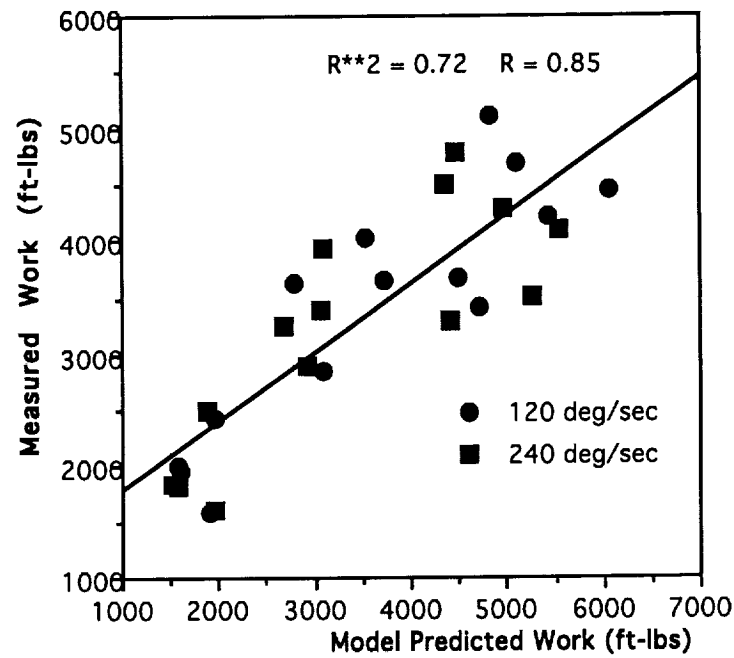


Figure 11. Model versus measured average torque produced for the ratchet wrench motion.

Ratchet Push- Model vs. Measured Work



Ratchet Pull - Model vs. Measured Work.

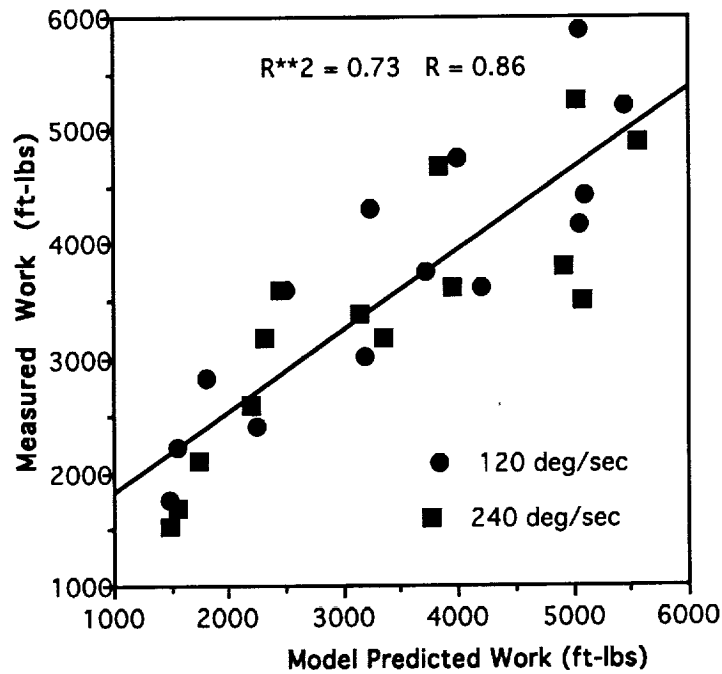
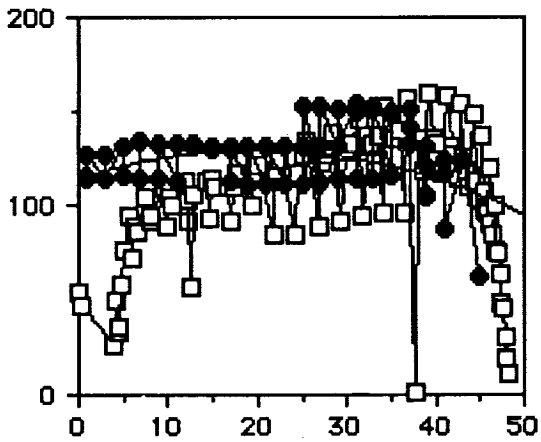


Figure 12. Model versus measured work produced for the ratchet wrench motion.

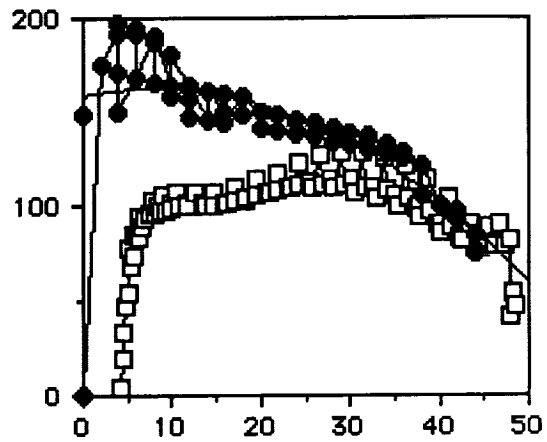
Figure 13 shows a plot of the actual versus model torques for a male and female for two extreme cases (strong male, weaker female). Trends in the data indicate that the model values are matched over a 5 to 40 degree range of the ratchet motion. The initial and final few degrees (0-5, 40-45 degrees) do not match our predicted results. These stages of the motion are related to the startup and slow-down processes involved [14] which are not currently part of our modeling effort. This result indicates that a similarity in magnitude and shape exists within most subjects. As shown in Figure 13 (part b, Male Push), some of the predicted torques are outside the measured range. This was expected. These inaccuracies could be due to nonmaximum trials, incorrect anthropometric measures, or setup discrepancies.

To get an estimate of the deviation from the measured data, a comparison computation was done. For each of the position torque data sets collected (Figure 13), a corresponding array of torque values was calculated from the model-predicted polynomial coefficients for that particular data set. A torque difference vector (a difference of the actual measured torque value at that angle and the computed value at that point from the predicted polynomial coefficients) was then created. A percentage absolute value (relative to the maximum) of the difference array was calculated and plotted. This same analysis was done on the regression coefficients computed from the measured data set. The regression coefficients from the measured data set represent the ideal curve through the collected data values.

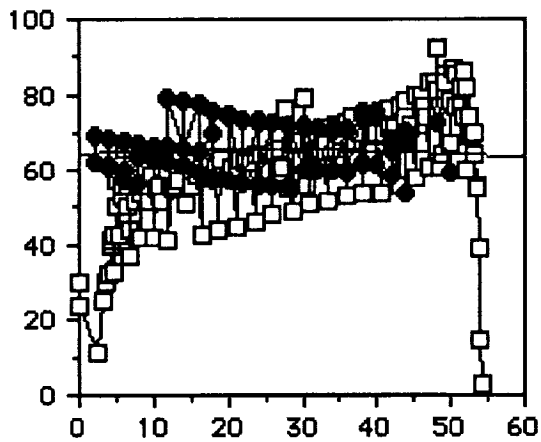
Figure 14 represents a comparison of the error of the measured regression coefficient and the error from the predicted coefficients relative to the original data. The difference (% error) in the regression coefficients from the original data reflect the fluctuation in the measured data. On average, there was a 7% deviation from the regression curve calculated from measured data. For prediction of second order regression coefficients, this is the best that one can hope to achieve because there is inherently that much variation in the measured data. As expected, the predicted coefficients have a greater deviation than the regression coefficients calculated from the actual data. The model deviations have an average of about 20%. This measure represents how closely (in absolute terms) the computed curve matches the measured data over the entire range.



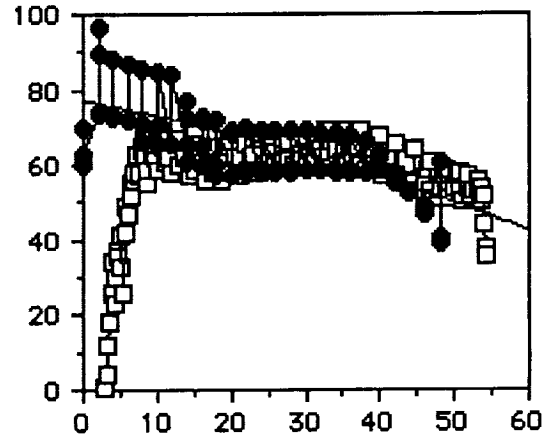
a. Male Pull



b. Male Push



c. Female Pull



d. Female Push

● Model Predicted
□ Measured Data

x axis = angular displacement (deg)
y axis = torque (ft-lbs).

Figure 13. Measured versus model values for ratchet wrench maneuver at a velocity of 120 deg/sec.

Model vs. Measured Polynomial: Absolute % Error as Compared to Measured Data

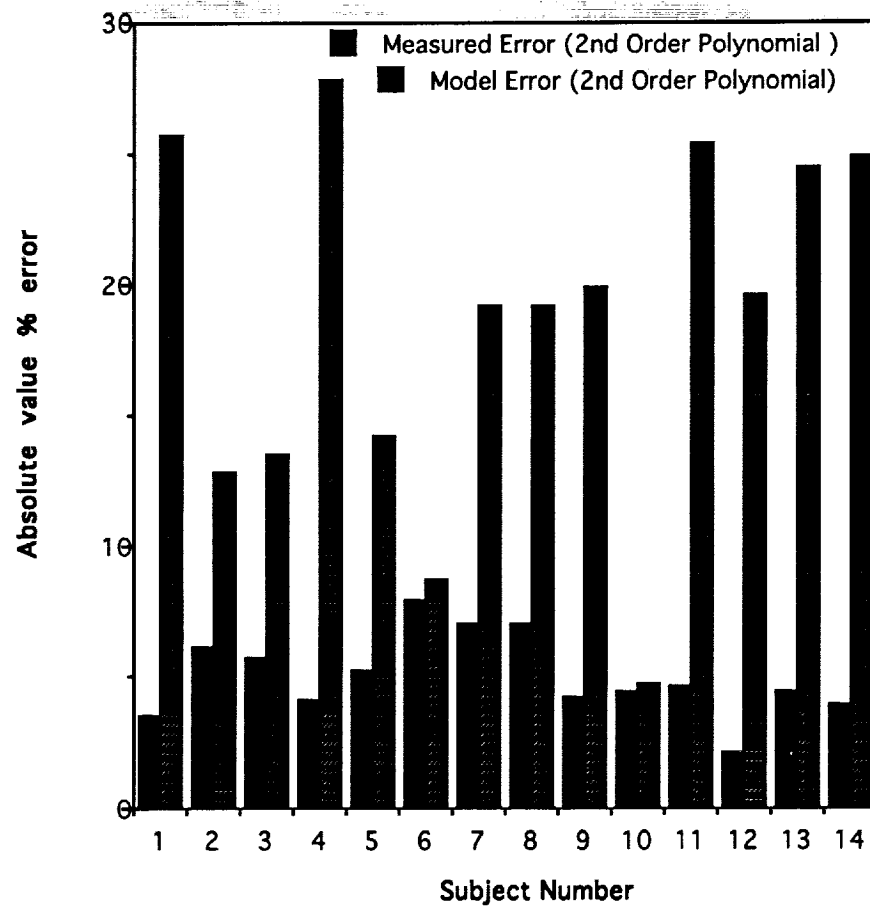


Figure 14. Chart comparing errors of polynomial fit of measured versus model data.

6.0 CONCLUSIONS

Unlike earlier attempts at strength modeling (based on rotational spring and damper systems) our model is based on empirical data. The shoulder, elbow, and wrist joints were characterized in terms of maximum isolated torque produced, or position and velocity, in all rotational planes for 14 subjects. This information was reduced by least squares regression into polynomial equations expressing torque as a function of position and velocity and tabularized for input to the strength model. This isolated joint information was used to compute (based on a vector sum algorithm and the subject's anthropometric measurements) forces resulting from composite motions—in this case, the ratchet wrench push-pull. Measured versus model output were compared.

Results indicate that forces derived from a composite motion of joints (ratcheting) can be predicted from isolated joint measures. Model versus measured values for 14 subjects were compared. T values calculated were well within the statistically acceptable limits ($\alpha = 0.01$), and regression analysis revealed the coefficient of variation (R^2) between actual and measured to be within 0.72 to 0.80. An estimate of the deviation of the model-computed polynomial from the measured data (over the entire range of motion) showed an average absolute deviation of 20%. The same analysis for a computed second order polynomial for the measured data, which represents the best case, showed a deviation of 7%.

These results indicate that the approach taken here at strength modeling is a viable one. Nevertheless, there are sources of error which need to be addressed. Anthropometric measurements and geometric figure creation, vital to the calculation and propagation of forces, need to be more accurate in terms of measurements taken, joint center location, and defined joint rotational axes. A more accurate velocity extrapolation mechanism is needed to remove the error of dynamic torque function look-up. Lastly, kinematic articulation of joints, which was used not only for proper orientation of the joint chain but also for the calculation of joint velocities, needs to be made more realistic.

7.0 FUTURE DIRECTIONS

Our overall objective is to incorporate into existing CAE capabilities a total body strength model of the NASA crewmember population for analytical physically based analysis. We will:

1. Continue to cycle through the phases of validation and refinement of the strength model with more complex motions.
2. Obtain additional isolated joint measures to extend our model to the whole body.
3. Incorporate the strength model into current inverse kinematic algorithms to produce more realistic reaching; i.e., strength guided motion [15, 16].
4. Apply the strength model to generate multiple gravity reach envelopes in all directions and axes and compare our results with measured data.

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